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Laser-assisted Milling of Advanced Materials

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Abstract

Advanced high-strength materials offer a huge application potential within highly stressed components in various industrial areas. But their machinability is still limited when applying established and conventionally available technologies. Aiming at the reduction of process forces, increased material removal rates and longer tool service life without application of cooling lubricants the Fraunhofer IPT has developed a novel process concept for laser-assisted milling with local laser-induced material plastification before cutting. The following paper comprises the novel process approach, fundamental process investigations, the design of a spindle-tool system with integrated beam guidance, laser control and first investigations with the new system.

Keywords: Laser-assisted milling; advanced materials; machining efficiency; process forces; tool wear

1. Introduction

The nowadays steadily increasing demands for innovations in the area of engineering science mostly result in rising requirements concerning the mechanical, thermal and chemical properties of highly stressed components. Resulting system and process requirements profiles more and more involve the application of advanced materials such as high strength steels, Ni-, Ti- or Co-base alloys and technical ceramics, e.g. silicon nitride (Si_3N_4).

1.1. Advanced high strength materials – applications and machinability

High strength materials offer a broad application potential from highly stressed forming tools in tool and die making industry, supporting structures or engine components in aerospace industry, components of gas turbines, medical implants or highly stressed components for plant and power engineering. Striving for more energy efficiency in plant engineering, air-craft and especially turbine industries there are three main trends observable: reduction of pollutant emission, resource conservation and the increase of fuel efficiency. These requirements are directly related to a higher thermal efficiency of the turbine and thereby to the gas temperature relation between the single compression stages. The higher the turbine inflow temperature and the higher the realized compression ratio the more efficient the turbine works. Use of high strength and temperature resistant materials like Ti- and Ni-base-alloys (e.g. Inconel) thus enable higher energy efficiency. These alloys are therefore often used in aircraft industries

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within light-weight-design at high alternating mechanical loads, e.g. in stiffener and carrier elements. In mould and die making industries for example the manufacture and maintenance cause 82% of the total product life cycle costs [1] due to resource-intensive production technologies like diamond-assisted grinding and frequent service due to intensive tool wear. In this context the local application of die inserts made of high strength materials at areas of large material deformation can significantly increase the tool service life by several times and therefore reduce the current maintenance costs. The local deposition of Co-base-alloys (e.g. stellites) with subsequent hard-machining guarantees the increased resistance of highly stressed local form elements like edges and curvatures. Especially Si_3N_4 ceramics offer exceptional wear resistance when opposed to abrasive stress as it occurs in metal forming operations such as deep drawing. Applying Si_3N_4 form inserts in deep drawing of stainless sheet metal steel can increase the tool service life by 5 to 100 times [2].

The cost-driving and technically restrictive factor in applying high strength materials such as Ti-, Co- and Ni-base-alloys and technical ceramics such as Si_3N_4 always is the significantly limited machinability with established and conventionally available processing technologies due to:

- Large process forces and high tool wear (flank wear)
- Extensive use of cooling lubricants (both in milling and grinding)
- Expensive process additives (diamond-based inserts or cutting edges and grinding tools)
- Poor rim zone qualities (micro cracking and flaking)
- Inefficient machining/ material processing (low material removal rates)
- Limited geometrical machining flexibility (change to alternative resource-intensive technologies, e.g. grinding)

Especially the use of advanced ceramics such as Si_3N_4 is still hampered by cost- and time-consuming end-machining causing up to 90% of the total production costs, although in different deep drawing applications for example the break even point when replacing conventional steel form inserts by ceramic inserts was reached in 0,5 to 2 years [2], depending on the specific use case. The essential challenge to fully utilize the potential of advanced high strength materials therefore is the development and supply of innovative, capable and economic machining technologies enabling the effective and finally productive manufacture of advanced components.

1.2. Laser-assisted hot machining

An effective possibility for improving the machinability of high strength materials is applying the principle of hot machining. Thereby the highly intense local input of thermal energy by a proper heat source such as focused laser radiation reduces the material strength and enables the efficient forming or the ductile material removal by conventional cutting processes such as turning and milling. Consequently, its reliable application requires a localized and controlled continuous heating of the material within the machining zone directly in front of tool contact. A decisive precondition is the decrease of material strength at elevated temperatures [3]. As a result of the relative movement between work piece and focal spot the required temperature profile is realized in the process area (area of plastic material deformation in forming and chip cross section in turning and milling) by heat conduction. Investigations on the temperature-dependent material behavior revealed a significant loss of material strength above a certain temperature level for both high-strength metal alloys and Si_3N_4 ceramic [4]. The substantial outcome of the resulting hybrid machining processes are reduced process forces and less tool wear (Figure 1).

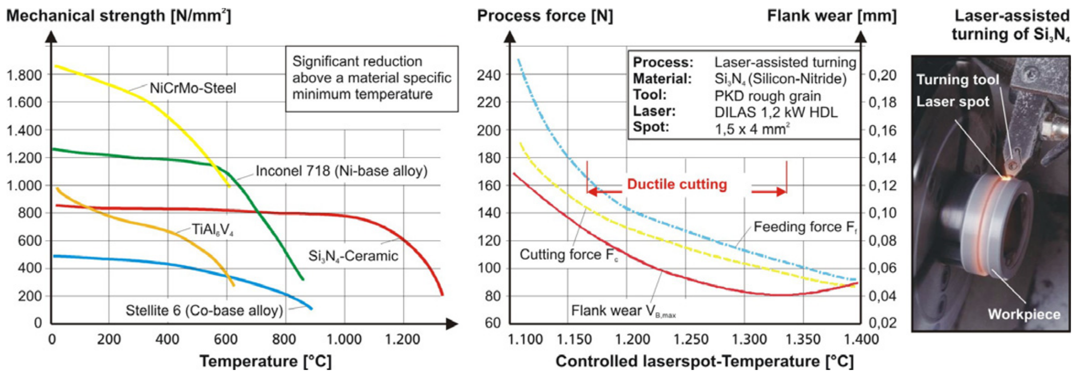

Fig. 1. Temperature-dependent mechanical properties of high strength metal alloys and Si_3N_4 ceramic; reduction of process forces and flank wear in laser-assisted turning of Si_3N_4 (for the manufacture of ceramic bearing rings)

According to investigations on conventional heating methods a sufficient energy density on the workpiece is essential for the efficiency and the feasibility of hot machining since otherwise the adequate material plastification cannot be guaranteed due to fast heat conduction [5]. In this context the application of intense laser radiation as thermal tool was revealed to be the most suitable heating method in hot machining. Additionally, modern fiber-coupled laser sources and laser system components further offer outstanding possibilities for the integration into conventional machine tools and production systems, opening up completely new applications [6,7].

2. State-of-the-art and preliminary research in laser-assisted machining

Hybrid manufacturing technologies such as ultra-sonic and laser-assisted machining offer high potential for increased production efficiency. First investigations on hot machining refer to the turn of the last century. Different methods were applied for preheating of the material prior to the machining operation such as heating by flame, friction, resistance and plasma beam. But all methods revealed considerable disadvantages concerning the resulting energy densities and the controllability of heat input. Later developed hot machining processes refer to the laser-assistance in cutting of carbides and technical ceramics by turning and milling as well as to the spinning of Ti- and Ni-base-alloys and to the shearing of sheet metals [8]. Concerning the heat source, providing fast end efficient material plastification, solid state lasers offer substantial advantages. Currently available systems provide a high power efficiency up to 40% at low maintenance. They enable the application of both transmissive and reflective optics, especially offering the flexibility of guiding the laser radiation through an optical fiber. The advantages of applying laser for hot machining have first been shown within investigations on laser-assisted turning of Ti- and Ni-base-alloys in the 1980's in USA, revealing reduced process forces and less tool wear. In addition to the analysis of laser-assisted turning processes [9] the first design concepts for the integration of laser system technology in turning lathes have been developed and implemented at Fraunhofer IPT [10]. Following, the Brite/Euram-project »Laser-Assisted Machining«, funded by the EU, dealt with the technological challenges and the resulting process and system requirements for the laser-assisted turning of Si_3N_4 ceramic and high strength steel [11]. A national project, funded by the German Federal Ministry of Education and Research BMBF, especially addressed the individual system requirements for the implementation of laser-assisted machining technologies and the application possibilities of laser sources as additional tools within modern and powerful machining systems [12,13].

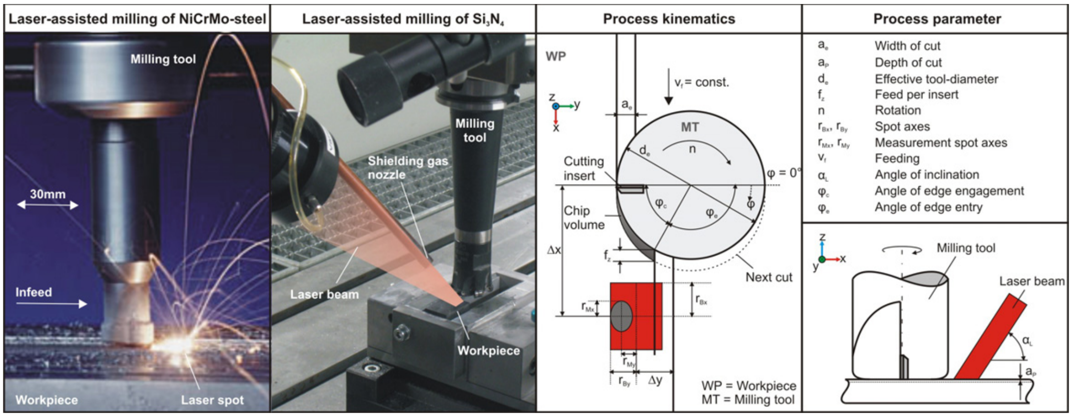

Fig. 2. Experimental set-up, process kinematics and process parameters in laser-assisted milling of a NiCrMo-steel and Si_3N_4 ceramic

For the implementation of hot machining the process area on the workpiece during cutting or forming is extensively and continuously heated and plastified by intense laser radiation which is focused onto the workpiece forward to the machining point (Figure 2). The thermally induced loss of material strength significantly increases the machinability concerning the achievable material removal rates or formability and tool service life. In the case of Si_3N_4 the highly intense laser-induced heat input causes a plastification of the sinter additives (glass phase) within the material structure. The amorphous glass phase, surrounding the silicon nitride crystals at the grain boundaries, demonstrates viscous-elastic behavior at increased temperatures. Therefore it reduces the deformation resistance above 1000°C and enables the machining of Si_3N_4 ceramic with geometrically defined cutting edge [14]. Only this material-specific effect enables the machining of Si_3N_4 with defined cutting edge [15] and causes no need for additional application of cooling lubricants in laser-assisted turning compared to the time and cost-intensive conventional machining by diamond-based grinding. The laser-assisted process further allows higher material removal rates at simultaneous prevention of micro and macro cracking on the workpiece surface which finally results in increased machining flexibility. In laser-assisted metal spinning the additional heat input and material plastification enables the manufacture of rotationally symmetric parts made of Ti- and Ni-based-alloys as well as strain hardening stainless steel within a single clamping. Contrary to conventional techniques, the laser-assisted forming operation considerably expands the formability and the forming limits of the materials and eliminates costly intermediate annealing steps. Compared to cold forming, the possible strain of e.g. stainless steel increases by 15 to 25% per spinning step. As additional bonus, the forming forces are reduced by up to 40% [16].

Despite its high potential for increased machinability laser-assisted milling has so far only been implemented within a test bench for fundamental investigations on the physical mechanisms of thermal and mechanical material interaction since there are currently multiple factors limiting the broad application (see kinematics in Figure 2):

- **No consistent thermally induced material plastification before cutting:**
  The laser radiation is projected peripheral to the cutting area onto the workpiece surface in front of the engaging milling tool. Therefore the required temperature profile in the chip cross section is realized by mainly heat conduction through the material. A huge amount of thermal energy is not be used for material plastification and transferred to the surrounding workpiece volume inducing stresses, deformations and limiting the machinability.
- **Insufficient machining flexibility:**
  Due to the inconsistent and limited material plastification in the chip cross section there is no possibility for complex trajectories and workpiece geometries. A consistent adjustment of geometry and position of the focal spot to varying machining conditions has not been possible yet. Therefore a sustainable temperature profile in the chip cross section could only be guaranteed for constant machining conditions, which is not possible for complex machining operations and its trajectories. Laser-assisted milling was thus limited to straight machining.

- **Insufficient process capability, process reliability and processing quality:**
  Due to the instable thermal conditions and the susceptibility to varying machining conditions as occurring in curvatures or workpiece edges the laser-assisted milling process mostly produces surface cracks and flaking.
- **No feasible system design concepts:**
  The design concepts developed and implemented so far consider external laser beam guidance, multiple additional axes enabling machining of curvatures and large amount of additional optics and drives which led to increased weight and reduced system dynamics. All recent designs covered huge installation space and limited the accessibility and machining flexibility, increased the system susceptibility to failure and caused further rising costs. Currently, there is no design concept available for the efficient use of laser-induced thermal energy within the chip cross section, providing a machining flexibility and capability comparable to conventional milling.

3. Novel technological concept for laser-assisted milling

Due to the current limitations and in order to close the existing gap between experimental stage and industrial application of laser-assisted milling the Fraunhofer IPT has developed and fundamentally investigated a novel process concept. The new concept is based on the energy absorption characteristics of the specific material enabling the defined heating and local softening of a discrete material volume. In contrast to the principle in Figure 2 the laser spot is not positioned peripheral to the cutting zone but directly projected onto the cutting surface of the respective chip volume inducing local material plastification before cutting. Heat conduction and the resulting temperature profile is barely influenced by geometric conditions but particularly by known or adjustable parameters such as:

- Energy absorption characteristic of the work piece material (particularly the depth and degree of absorption)
- Laser and machining parameters (in particular the laser power, spot geometry, feed rate and cutting speed)
- Projection of the laser spot at a certain forward distance to the engaging cutting edge (allows the precise adjustment of heat conduction and material plastification depending on the respective material properties)

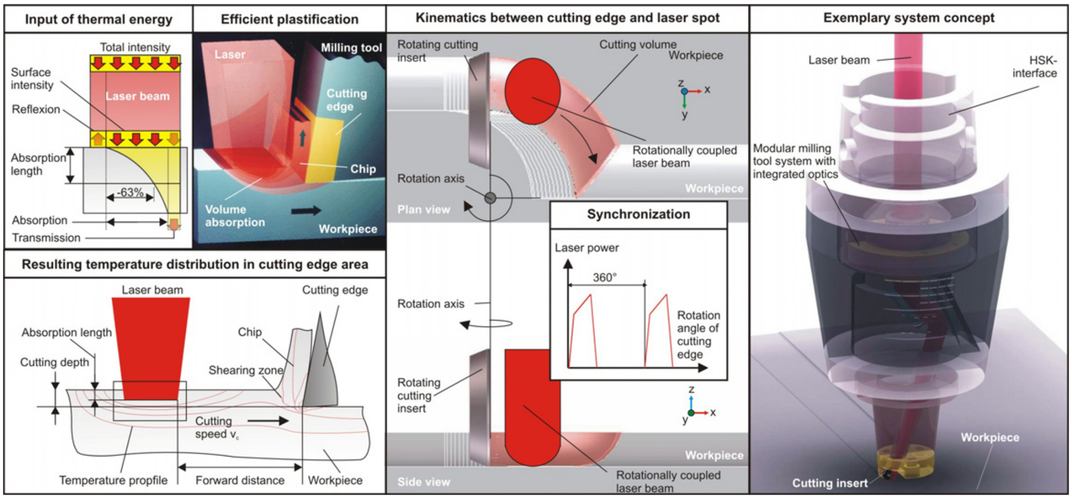

Fig. 3. Technological concept for the local heating and plastification of the chip volume before cutting; synchronization between laser beam projection and rotating cutting edge; system concept with optical and mechanical system components integrated into an HSK tool interface

Figure 3 illustrates the process kinematics and an exemplary system layout for the laser beam guiding through an HSK tool interface (hollow shank taper). The illustrated concept has been established at Fraunhofer IPT and enables the tool integrated laser beam projection and focusing. Thereby the laser beam is directly projected onto the cutting surface in the machining area. Positioning between cutting edge and laser spot can be variably adjusted in order to set specific heat conduction before cutting. The resulting material plastification is mainly limited to the respective chip volume. Consequently, the input of thermal energy into surrounding material areas is reduced to a minimum. According to the local and specific material plastification of the chip the laser projection must be synchronized with the rotating cutting edge in order to avoid the heating and thermal impact on already machined work piece material.

4. Fundamental investigations on the novel concept by laser-assisted cutting of Si_3N_4 ceramic

Based on the novel process concept the Fraunhofer IPT has implemented an experimental set-up to qualify the feasibility of the laser-assisted machining process with local and specific heat input into the chip volume. According experiments with Si_3N_4 were conducted on an ultra-precision machine tool with adjustable laser beam parameters and integrated measurement of the resulting process forces. Related experiments have been performed on a planing machine (fly cutting) within constant climate conditions in order to adjust and investigate highly precise tool feeding. The rotational motion in milling was thereby transformed to a nearly translational process with direct laser beam projection in front of a static cutting edge by clamping the work piece onto a hydrostatic rotary table (c-axis).

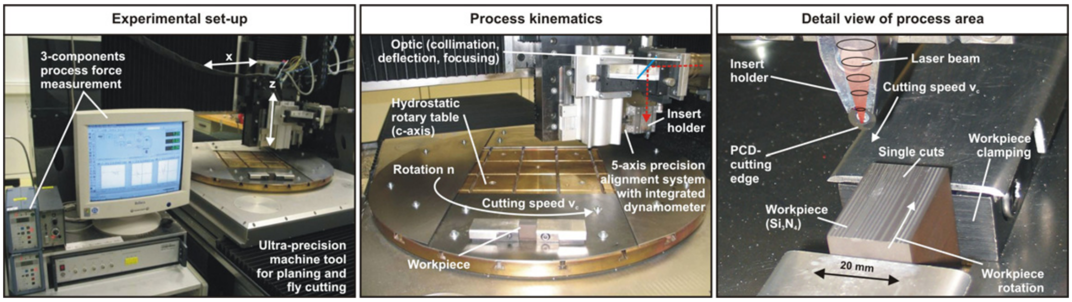

Fig. 4. Experimental set-up for the process force measurement and testing of the novel concept through laser-assisted planing with single cuts

For enabling 3-components force measurement and high precision beam adjustment in relation to the moving workpiece a dynamometer has been integrated into a 5-axis alignment device carrying the insert holder. Experiments revealed that the proper positioning of the laser spot relatively to the cutting edge in combination with suitable process parameters leads to significantly reduced cutting forces and energy input into the workpiece material, thus minimizing surface flaking, crack formation and material distortion. According process analyses varying the positioning of the laser spot relatively to the cutting edge, cutting speed, cutting depth and laser power indicated outstanding and very promising results concerning the machinability of the material (see Figure 5):

- Cutting force values could be reduced by up to 80 % compared to dry machining without laser-assistance
- Material removal rates could be multiplied by up to 160 times concerning surfaces without damages (cutting speed and chip thickness could be increased simultaneously)

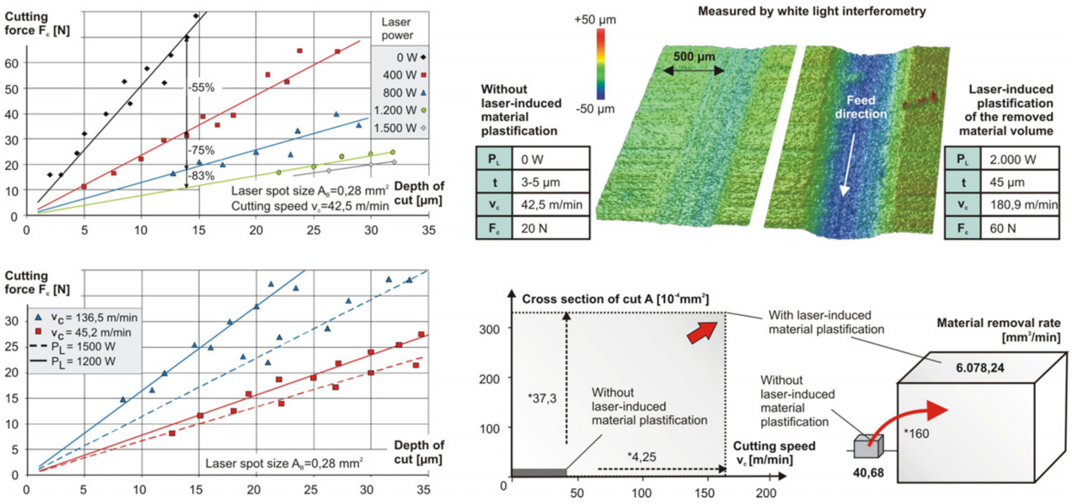

Fig. 5. Current limits of the hybrid cutting process according to the novel concept for laser-assisted machining; reduction of process forces and increase of process efficiency compared to conventional dry machining without laser-assistance (concerning surfaces without damages)

All investigations have been carried out on gas pressure sintered Si_3N_4 cuboids (GPSN) 30*20*30 mm^3 with 10 weight percent sinter additives (glass phase). They were machined with polycrystalline diamond tool inserts (PCD) varying laser power, cutting speed, feed rate, cutting depth and contact width. Apart from laser power the feed rate is decisively affecting the process forces and resulting surface quality. As the position of the laser focal spot particularly affects the temperature profile in the chip cross section the distance between focal spot and tool contact (beam forward distance) must be minimized to widely keep the temperature and plastified material condition and to avoid a recooling of the machining zone by convection and thermal conduction into the surrounding workpiece material volume. However, forward distances might additionally impair the tool service life via excessively high temperatures at the workpiece surface as well as reflected laser radiation on the milling tool. Due to the differing engagement conditions the analysis of tool wear was initially neglected within the preliminary process studies.

5. Machining system for laser-assisted milling of advanced materials

5.1. Design of a hybrid spindle-tool-system

Based on the described approach of direct laser beam projection onto the cutting surface the design aims at equipping a conventional AC-motor spindle with optical and mechanical system components to enable the flexible laser beam guiding and forming through the hollow spindle shaft. Figure 6 shows the fundamental system design concept with a laser beam guiding, that is integrated into the spindle design. Since the laser radiation emerges divergently from the fiber a collimation unit first forms the laser radiation by one aspheric lens to a nearly parallel beam which propagates through the hollow rotor shaft. The collimation unit was developed in close collaboration with Sill Optics. It forms and constricts the emerging radiation before it coaxially passes through the hollow rotor shaft and the manual clamping system up to a tool-integrated focusing unit where the laser beam is finally deflected via two hr-coated (high reflection) mirrors on the cutting surface, directly in front of the rotating PCD-cutting edge. By the precise relative fine positioning of the aspheric lens towards the fiber ending coaxially to the rotation axis the geometric beam propagation parameters such as beam aperture and beam divergence angle can be modified within a certain range which allows for the flexible focusing onto the work piece. As a result, the laser parameters can finally be adapted to the current process conditions and cutting kinematics by means of a projected laser spot diameter on the cutting surface within the range of 0.45 to 2.8 mm. A fiber-coupled high power fiber laser source (1070 nm) is connected to the spindle housing via an adjustable opto-mechanical interface, precisely aligning the optical fiber end towards the hollow spindle shaft. It is precisely attached to the spindle housing and combines both the adjustable guiding of the laser beam through the rotor shaft and the supply of process gas via a rotary feedthrough. The feedthrough system further provides the necessary gas flow to the tool for the cooling of thermally loaded optical and mechanical components, for shielding contaminating particles which emerge from the cutting process and for the improvement of the thermal process efficiency by the immediate removal of process particles out of the beam path. Due to this tooling concept a conventional spindle system can be flexibly equipped with milling tools of different geometric dimensions and aspect ratios for a wide variety of machining operations. The modular system design with optical and mechanical interfaces (QD-fiber interface, HSK-100 C tool interface[hollow shank taper]) thereby guarantees the fast and easy accessibility to all decisive system components of the collimation unit, the spindle and the milling tool, as well as the scalability of all system modules, e.g. dimensions and aspect ratios of the milling tools, and further enables the fast and easy adjustment of laser beam parameters.

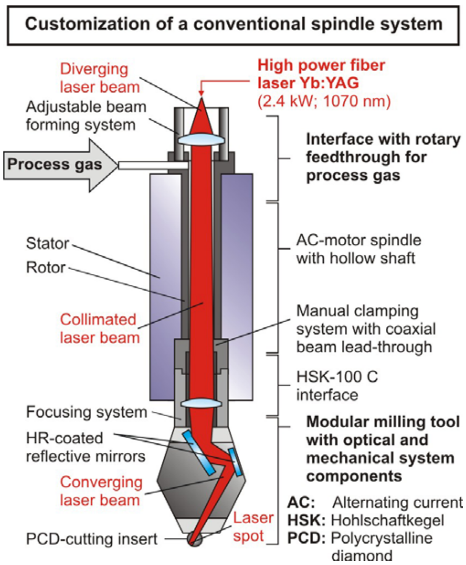

Fig. 6. System design concept of a conventional motor spindle with modular optical and mechanical system components and interface for the laser-assisted milling of advanced materials

A minimal amount of complex system components and the compact design guarantee high system robustness and reliability. Figure 7 shows an exemplary design concept for the optical system components within the tool-integrated beam guiding system. The design concept for the milling tool features integrated high power beam transmission and a gas flow system. Optical system components such as safety glasses, lenses, brass tubes and fixtures are integrated into an optical module of an HSK-100 C interface, suitable for high power applications up to several kW laser power. Even though the absorption of thermal energy resulting from direct and scattered laser radiation is very small, the high level of beam power requires the efficient cooling of all optical and mechanical components. Thermal protection is ensured by a special gas cooling that additionally minimizes the thermally induced focus shift caused by the distortion of the optical substrate in lenses and mirrors. After the laser radiation passed the spindle shaft it is focused to a converging beam, which, reflected by two mirrors, finally propagates into the process area up to the cutting surface of the work piece. With respect to the resulting thermal intensities on the surface both mirrors are made of fused silica offering outstanding thermal and mechanical stability. The substrate is covered by a customized high reflection coating for 1070 nm wavelength. Since the beam energy is almost entirely deflected to the process area only a small fraction is absorbed by the mirror and induces thermal load. The resulting thermal energy is finally conducted by the fixtures either to the surrounding gas flow or the adjacent housing. Due to the thermal loads and the implied heat dissipation the housing is made of invar-steel, a thermally neutral material that provides negligible thermal expansion. The material design thus ensures minimal structural distortion during the laser process and provides stable optical transmission conditions for the continuous precision alignment between laser spot and rotating cutting edge.

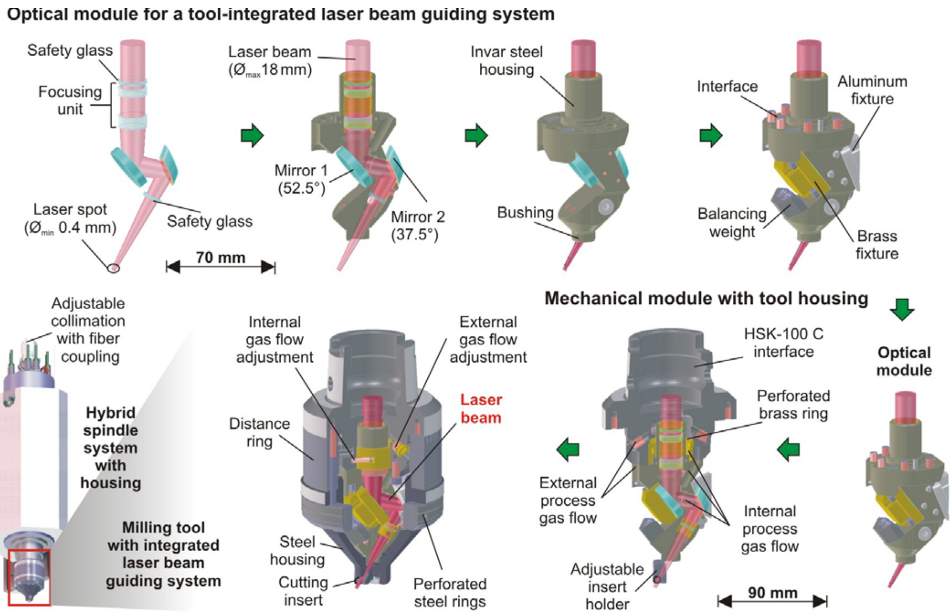

Fig. 7. Design concept of an HSK-100 C milling system with integrated optics for high power beam transmission; integration of the optical module and the flow system for the supply of process gas (illustrated as 2-lens-system for beam focusing)

Because of the necessary system balance the design of the optical module also involves features like balancing weights, balancing drills and fixtures with different material densities for the deflection mirrors. Additionally to the thermal loads the interrupted cutting induces vibrations and local mechanical load which both are transferred through the entire tool system. These vibrations and loads could affect the optical system and thereby deteriorate the stability of the hybrid process. Separating the mechanically loaded tool housing and the optical module minimizes the mechanical and thermally induced distortion of the tool structure. The whole system design concept thus ensures precision and form stability for the machining process with varying thermal and mechanical process conditions. In this context the gas cooling does not only serve for the thermal protection of system components. It further enables two decisive extra functionalities: First the internal gas flow through the invar housing is finally released coaxially to the propagating laser beam and directed towards the cutting surface through a respective gas nozzle. The continuous gas flow avoids the contamination of the reflective mirrors and the focusing unit by preventing the produced process particles from entering the laser beam lead-through drilling (see Figure 8).

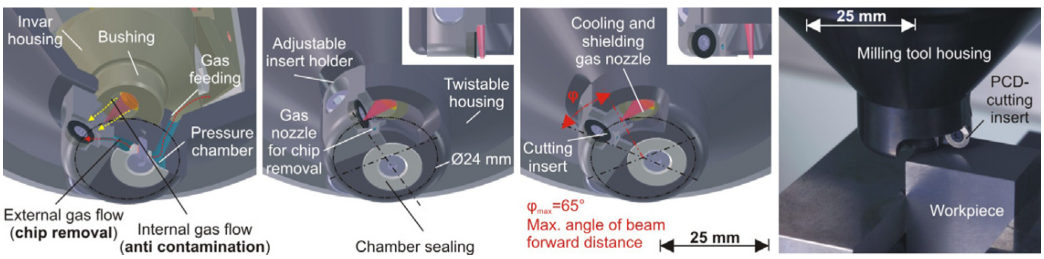

Fig. 8. Detailed system design of auxiliary devices for shielding, cooling and chip removal by process gas; variable laser beam forward distance for adjustable material preheating and plastification; picture of implemented tool design

As it blows the process particles out of the beam path the gas flow also creates a shielding effect and thus further improves the energy absorption in the cutting surface. The shielding effect is additionally supported by a second gas flow emerging from a small gas nozzle, which is always directed towards the cutting edge. Beside the immediate chip removal from the cutting zone the second gas flow also reduces the thermal load of the cutting edge by additional heat conduction. Therefore the separated gas flow is led through a hole to a pressure chamber before it emerges towards the cutting edge. Due to the division of the gas channel system into external and internal gas flow the size of resulting heat releasing surface areas is significantly enlarged. This implies a high rate of heat convection to the surrounding gas flow, resulting in maximal cooling effect.

5.2. System integration

All laser system components, the machine spindle, and the milling tool were assembled and integrated into a 5-axis machining center (3+2-axes-kinematic) with combined real-time control exclusively provided for the laser-assisted machining of advanced materials. In addition to the optical and mechanical components a camera-based monitoring system has been integrated since the workspace area is completely closed during laser-assisted machining for safety reasons. A piezo-based process force measurement further enables fundamental process investigations with embedded force measurement. The integration concept and technical specifications of the spindle system and the 5-axis machining center are shown in Figure 9.

Fig. 9. Integration of all system and control components into a hybrid 5-axis machining center for laser-assisted machining of Si_3N_4; technical specifications of the spindle system and the machining center (laser source and fiber-coupling are not shown in the picture)

6. Laser process control and synchronization with the machining operation

6.1. Edge engagement kinematics

Knowing the geometry of the milling tool and the current kinematic engagement conditions of the rotating cutting edge is the decisive precondition for the continuous and controlled local heating and plastification of the chip volume. In this context the synchronous laser process control involves the exact modeling of the kinematic and geometric tool and edge engagement conditions within every single edge rotation. The synchronization of the switch on/off points of the laser requires the determination of entrance and exit angle of the rotating cutting insert in the workpiece. Furthermore, the laser power has to be continuously adapted to the current material volume that is covered by the laser spot, consequently plastified and finally removed by the engaging edge in order to ensure a homogenous material plastification. These demands necessitate the dynamic calculation of the chip thickness, which is continuously varying over edge rotation and tool feeding depending on rotation speed and feed per insert. Thereby the laser-induced input of thermal energy happens within the resulting angular range of edge engagement according to Figure 3, whereas the laser source is switched off when the rotating edge is not engaged in the workpiece volume. Based on the machine coordinates, the tool dimensions, tool feeding and the width of cut the required process angles can be calculated with the given geometric conditions and kinematic dependencies. In order to synchronize the angular values with the spindle rotation, all angles are referred to a virtual point zero which is stationary through the rotary encoder in the spindle housing, representing an absolute reference.

All calculations can be adapted to complex machining trajectories via discretization and subsequent transformation to a workpiece-corresponding coordinate system according to the general engagement conditions within a curved 3D trajectory profile (Figure 10).

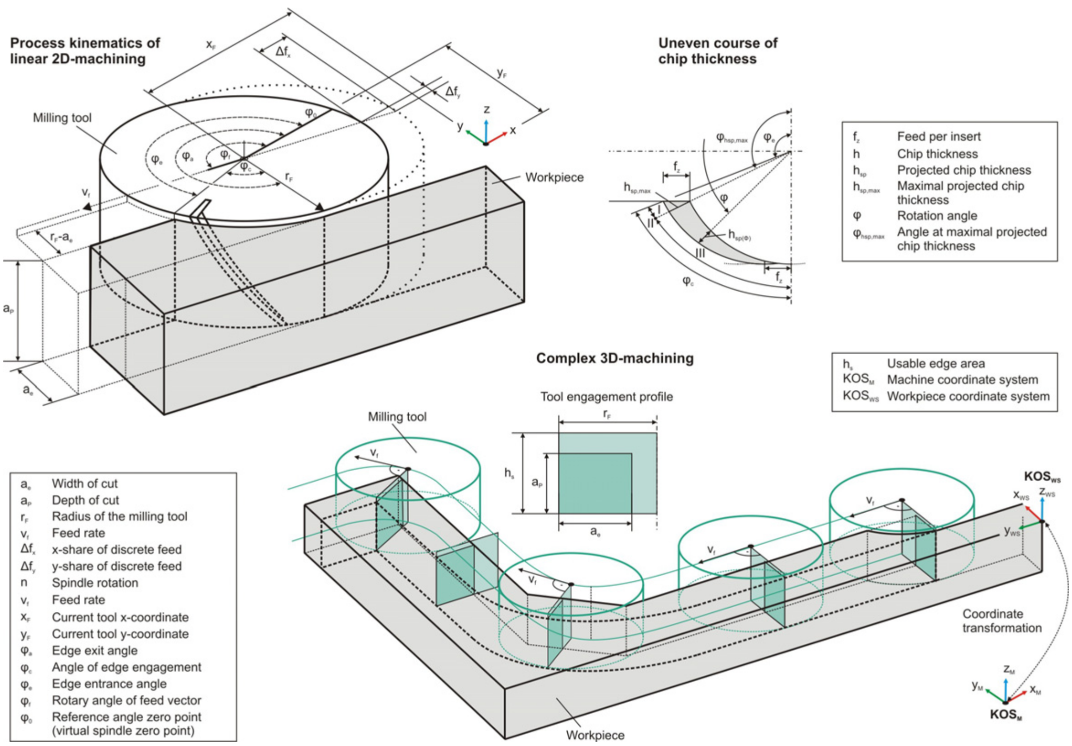

Fig. 10. Tool and edge engagement conditions and process kinematics in linear 2D and complex 3D machining operations; uneven course of chip thickness (exemplary straight face milling of cuboids); tool engagement profile in complex milling operations within curved 3D trajectories

In addition to the linear and nonlinear shares of the trajectory course there are also discontinuous processes at the beginning and at the end of machining, when the tool and its rotating insert are first engaging into the material volume and at its exit. Up to the stage of full engagement the angle of edge exit and edge engagement are continuously rising, the angle of edge entry remains constant, vice versa at the end of machining (face milling).

6.2. Calculation of chip thickness

The trajectory in climb milling is based on the superposition of translational feed rate and rotational velocity of the cutting edge. The resulting trajectory describes an extended cycloid, the so-called trochoid [17], whereof the coordinates of the trajectory [18] and the general equation for the trajectory in climb milling can be derived. As one of the most important process parameter in terms of process forces, edge load and resulting wear behavior of the cutting insert the current chip thickness, determining the implied chip volume which is covered by the projected laser spot, can be derived from this trochoid at all times and represents the decisive factor for the laser power set point value. The course of the chip thickness can be divided in three areas (see Figure 10) with an infinitesimal small circular arc in area I, that can be estimated as straight, the peak in II with maximal chip thickness and the area III as the longest period of edge engagement, which cannot be determined explicitly. But it is possible to approximate the chip thickness by an implicit function [19], which can finally be solved by multiple approximation methods differing in terms of accuracy and simplification:

- Fischer [20] neglects the translational shares of feed rate whereby the resulting trajectory is not a trochoid anymore but a simple circle with the radius of the milling tool. Therefore it can only be used as rough approximation for relatively small values of feed rate since the resulting relative error quickly exceeds 2-10%.
- The approach from Martellotti considers the cycloidal course of the engagement curve and both the rotational and translational velocity of the milling tool. For small feed rates the approximation from Martellotti merges into the approach from Fischer, but the relative error is significantly reduced to about 0,5-2%.
- Further increase of approximation accuracy can only be achieved by the measurement of the dynamic behavior during tool engagement [21]. Thereby a maximum relative error of 1% becomes possible. But it is necessary to acquire all process parameters, in particular the process forces. That is why this approach is not feasible for industrial applications.

Especially in laser-assisted milling of advanced materials with respectively small feed rates the approach according to Martellotti with a maximal relative error of less than 1% is sufficient. It is used for the dynamic determination of chip thickness and the subsequent calculation of laser power set point value (Figure 11).

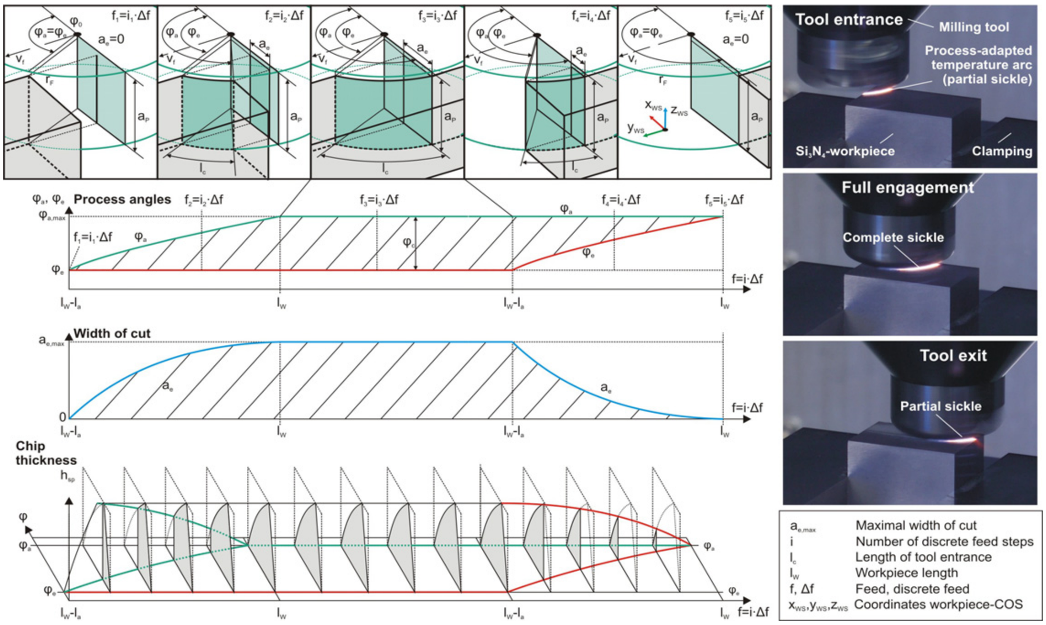

Fig. 11. Qualitative course of chip thickness, process angles and width of cut for continuous and discontinuous process stages within the laser-assisted milling of Si_3N_4-ceramic cuboids according to the approximation approach from Martellotti; process pictures without material removal

6.3. Dynamic synchronization and laser process control

Based on the calculated chip thickness and the chip cross section the current material volume, that is covered by the laser spot, can be calculated according to DIN 6580. In dependence on the angular range of edge engagement the covered partial chip volume can thus be used for the calculation and online-adaptation of laser power set point values. The high demands concerning calculation speed and efficiency will be guaranteed by proper real-time control hardware with sufficient capacities for all time-critical requirements. Due to the application of generally accepted interfaces the whole system concept is easily adaptable to other machine configurations and laser systems.

7. First process results with the novel machining system

First experimental investigations with the new machining system conducted on Si_3N_4-ceramic confirmed the preliminary results from previous experiments on laser-assisted cutting as described in chapter 4. Resulting process forces were reduced by 73-90%. In addition to the process forces the wear of the PCD-cutting insert was also significantly reduced. Conventional milling without laser-assistance produced large flaking at the insert edge whereas the laser-assisted process revealed only little edge and flank wear. The resulting functionality and benefit of the novel technological concept for laser-assisted milling with local plastification of the chip volume by spindle and tool-integrated beam guiding could be proven by these first experiments (Figure 12). Further process analysis will provide the necessary understanding and parameter ranges for different materials and machining conditions.

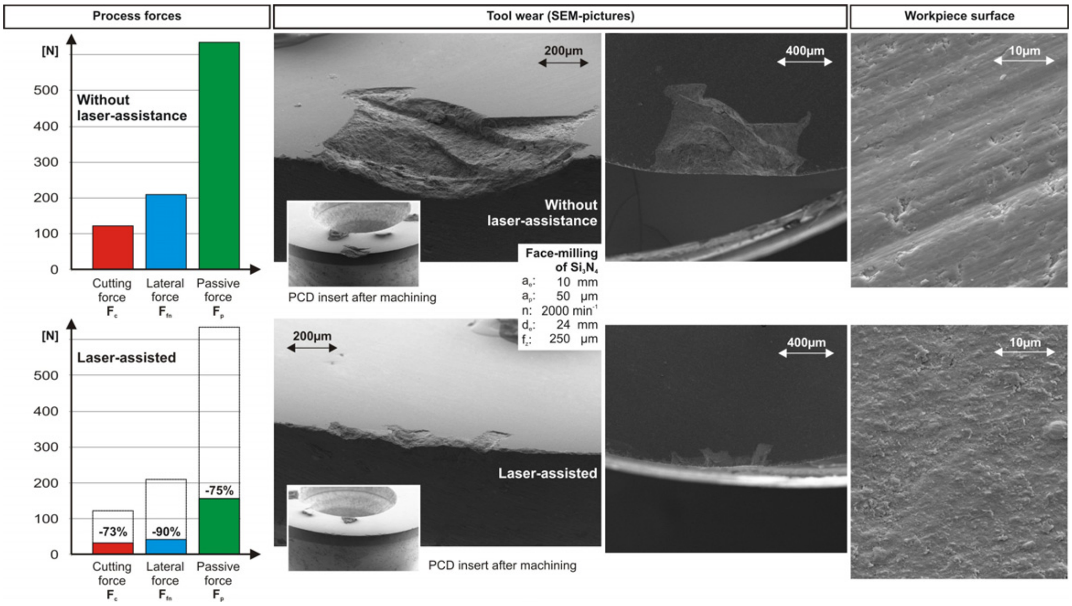

Fig. 12. Results of the first process investigations on laser-assisted milling of Si_3N_4 with the novel machining system

8. Summary and outlook

The described research activities and developments build a very promising basis for the significant increase of process efficiency and machining flexibility in laser-assisted milling of advanced materials, whereby the illustrated technological approach has been realized within a production-ready machining system, qualified for industrial application. The presented work is based on a novel technological approach for efficient laser-induced material plastification during milling. After fundamental and very promising process analysis a spindle-tool-system with integrated optics for laser beam guiding and forming has been developed and integrated into a 5-axis machining center. Based on the complex kinematics a control system dynamically determining the resulting chip thickness in climb milling, that continuously calculates the necessary laser process parameters adapted to the current machining conditions, has been realized and applied in machining. Further research and development in the field of laser-assisted milling will comprise the machining of other materials including different high strength metals, detailed investigations on process parameters and their influence on machinability, definition of the most feasible parameter constellations, the manufacture of demonstrator geometries and industrially relevant demonstrator parts as well as the realization of a CAD/CAM-module enabling the application of the hybrid process within flexible 5-axis machining. The presented and addressed work will thus enhance the economic usability of advanced and difficult to machine high-strength materials by providing an efficient, powerful and productive milling technology.

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